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Research article

# Comparison of volumetric loss and surface roughness of composite dental restorations obtained by additive and subtractive manufacturing methods

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ABSTRACT

*Statement of problem:* Permanent crown materials produced with new generation additive manufacturing and traditional subtractive manufacturing materials have not been compared in terms of wear resistance.

*Purpose:* This study aims to compare the volumetric loss related to wear and resulting surface roughness after aging in a chewing simulator between resin nano ceramics produced with milling technique and permanent crown materials produced with three dimensional (3D) printing.

*Materials and methods:* Three different hybrid composite-ceramic (HCC) (The three materials are GC: Cerasmart, VE: Vita Enamic, and GV: Grandio Voco.) and one 3D printed definitive crown resin (FormLabs Permanent Crown Resin) were investigated before aging (n:8), the surface roughness of all samples was measured with a profilometer, and 1 randomly selected sample from each subgroup was imaged with scanning electron microscope (SEM). 3D scans of each sample were obtained with a desktop scanner. Thermomechanical aging was performed using a chewing simulator. Four hundred thousand cycles were completed under a vertical occlusal force of 49 ± 0.7 N with a thermal cycle of 1.7 Hz 5–55° and with a dwell time of 120 s, mimicking 2 years of aging. The imaging procedures were repeated, and the change in surface roughness was evaluated. 3D images were also overlapped, and the volumetric loss was calculated with the relevant inspector software. The data obtained were analyzed by two-way ANOVA ($p < 0.05$).

*Result:* The results showed significant statistical differences for both parameters ($p > 0.05$). The highest volumetric loss was found in the GV group while the lowest volumetric loss was in the VE group. The highest surface roughness values were observed in the GV group, while the lowest values belonged to the VE one.

*Conclusion:* Of the restorative materials evaluated, the VE group is suitable for long-term restorations, whereas the GV one is suitable for medium-term restorations. It is promising in terms of 3D printing technologies that the 3D material gives comparable results with the GV group.

*Clinical implication:* Additive manufacturing techniques are a successful method that accelerates the manufacturing process. Permanent crown resins are promising alternatives to conventional production.

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**Table 1**
Description of study groups.

| Material | Symbol | Classification | Contents | Manufacturer |
|---|---|---|---|---|
| Vita Enamic | VE | Polymer-Infiltrated Ceramic | 86% Feldspathic, 14% Polymer | Vita Zahnfabrik, Germany |
| GC Cerasmart | GC | Resin Nano Ceramic | 71% Silica and Barium Nanoparticles, 29% Composite Resin | GC Corporation, Tokyo, Japan |
| Grandio Voco | GV | Resin Nano Ceramic | Content information was not found. | Voco GmbH, Cuxhaven, Germany |
| FormLabs Permanent Crown Resin | 3D | Biocompatible Photopolymer Resin | Content information was not found. | Somerville, MA, USA |

## 1. Introduction

In recent years, the rapid development of dentistry has transformed certain procedures into clinical routines of prosthetic dentistry using computer-aided design and manufacturing (CAD/CAM) systems. In CAD/CAM systems, restoration production techniques are generally performed through two methods. The first one is the conventional subtractive method, which involves the abrasion of prefabricated blocks using mills and discs, a method used from the past to the present. This method is also referred to as the 'subtractive method.' Additive manufacturing, on the other hand, refers to the production of three-dimensional objects by adding layers of a specific material such as metal, porcelain powders, liquid resin, etc. [1].

Physiological tooth wear is a normal process during one's lifetime, and it highlights the need for improved chewing efficiency and reduced susceptibility to tooth disease and malocclusion. Wear is a consequence of occlusal interactions that are considered normal. If it is not controlled, however, wear can lead to reduced chewing ability, decreasing the quality of life and potentially deteriorating overall health [2,3]. Ideally, restorative materials should undergo wear in the same way as natural dentition [4]. While the literature describes many methods for assessing wear, advances in digital technology are now making the three dimensional (3D) measurement of progress the gold standard [3].

Wear is mainly attributed to the particle size of the materials tested and the way the particles are packaged. In addition, the water absorption capacity and inorganic percentages of the materials also affect the wear patterns [4–11]. Determining the wear patterns of current restorative materials will prevent additional costs by reducing restoration renewals due to incorrect material selection; it will also result in more successful restorations.

Another parameter that affects the clinical success of composite restorations is surface roughness. Rough surfaces in the mouth due to long-term use will primarily cause plaque accumulation and subsequent restoration failure [12–15]. For this reason, composite restorations with minimum surface roughness in the mouth for a long time are desired.

Resin composite restorations fabricated with subtractive manufacturing provide an important alternative to direct restorations [16]. Composite material technology has advanced significantly in recent years, mostly due to the increasing aesthetic demands of patients [17].In addition, hybrit ceramic composites (HCC) have become more popular in dentistry due to the improved physical and mechanical properties of composite materials, the increase in dentists' familiarity with these materials, the high cost of ceramic systems, and the wear these systems cause on the opposing tooth [4,17].They enable reliable restorations with accurate dimensions, reducing fabrication time and labor compared to direct manufacturing techniques [18]. However, since milling systems are based on the principle of cutting solid blocks to obtain the desired shape, some material is wasted, and extra costs for milling tools result [19].

Initially, additive manufacturing technology had limited applications in dentistry due to certain issues, including the durability of materials, manufacturing accuracy, processing speed, and overall cost. Improved print accuracy, increased variety of materials, smaller and more accessible 3D printing devices, and the acceleration of development due to the expiration of the patent period of the existing systems have made this technology more widespread in clinical applications [20,21]. In addition, these systems, which do not waste material in the fabrication of much more complex shapes, are more economical than subtractive manufacturing techniques with regards to investment in hardware and total production costs, thus reducing its carbon footprint [19].

Many groups of materials may be used with 3D printing, including metals, ceramics, and resin. Resin-based materials were first used in the manufacture of temporary prostheses. Nowadays, they are available for base material, splint material, permanent inlay, onlay, and crown restorations. Some studies report that the occlusal stress distribution of new resin materials is suitable for long-term use and has a high level of durability under occlusal loads [22,23]. While permanent crown resin is only available from a few brands, restorations are typically fabricated layer-by-layer with a 3D printer using photopolymerization methods, such as digital light processing (DLP) and stereolithography (SLA).

The main parameters limiting the use of 3D print manufacturing in clinical applications are aesthetic appearance, roughness values, wear resistance, and dimensional accuracy [20–26]. Due to the contemporary characteristics of the materials, the literature on the comparison of wear values of composite restorations fabricated with subtractive manufacturing and composite samples obtained with additive manufacturing techniques is insufficient. Therefore, the present study aims to compare the surface roughness and wear-related volumetric losses of 4 composite types fabricated with different manufacturing techniques (Three different subtractive manufactured HCC materials and one additive manufactured permanent crown resin).

The null hypotheses were that (h1) no significant differences in volume loss, and (h2) surface roughness between the four groups.

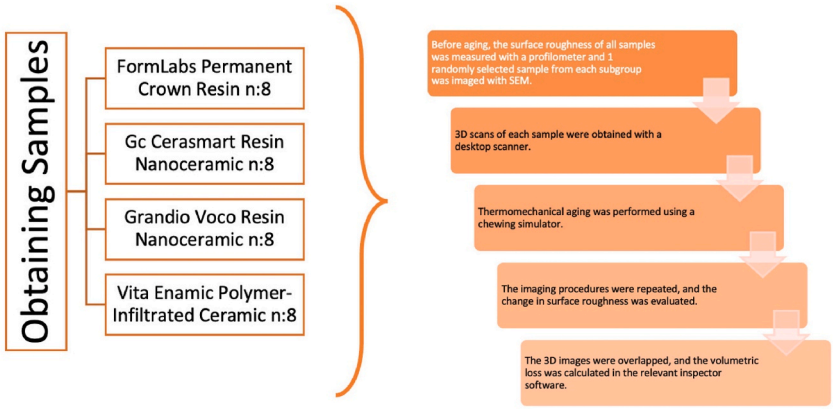
Obtaining Samples
FormLabs Permanent Crown Resin n:8
Gc Cerasmart Resin Nanoceramic n:8
Grandio Voco Resin Nanoceramic n:8
Vita Enamic Polymer-Infiltrated Ceramic n:8
Before aging, the surface roughness of all samples was measured with a profilometer and 1 randomly selected sample from each subgroup was imaged with SEM.
3D scans of each sample were obtained with a desktop scanner.
Thermomechanical aging was performed using a chewing simulator.
The imaging procedures were repeated, and the change in surface roughness was evaluated.
The 3D images were overlapped, and the volumetric loss was calculated in the relevant inspector software.

**Fig. 1.** Illustration of the methodology of the present study.

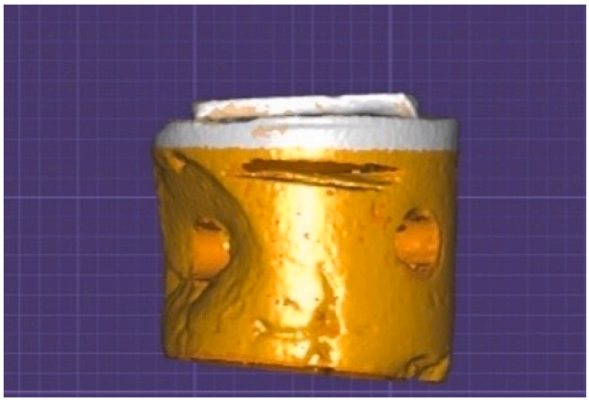

**Fig. 2.** Scanning of the sample with exocad Smartoptics x4 before aging.

## 2. Materials and methods

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### *2.1. Materials*

Three different subtractive manufactured HCC materials and one additive manufactured permanent crown resin were investigated. The total sample size for the current study setup was analyzed at a sensitivity of 0.45 and a power of 80%. The analysis tool G*Power v3.1.9.2 was used with four test groups based on an estimated significance level of $p = 0.05$. The total number of samples was 32 (n:8). The materials were GC: Cerasmart (GC Corporation; Tokyo, Japan); VE: Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany); GV: Grandio Voco (Voco GmbH, Cuxhaven, Germany); and 3D: FormLabs Permanent Crown Resin (FormLabs Somerville, MA, USA). The main characteristics of the materials are given in Table 1.

The methodology of the present study is described in Fig. 1.

### *2.2. Specimen preparation*

For each type of composite HCC material (i.e., GC, VE, and GV), 8 samples (14 × 14 × 2 mm in size) were prepared using a low-speed precision saw (IsoMet Low-Speed Saw, Buehler, IL, USA). Samples from composite blocks were polished under water cooling with #600 to #1200 silicon carbide (SiC) papers (3 M ESPE, St Paul, USA).

The samples for the 3D group were printed with the SLA 3D printer Form 2 (FormLabs, Somerville, MA, USA). Using the device Otoflash G171, they were then light cured with an illumination exposure of 4000 lux under an atmosphere consisting of nitrogen oxide gas. All the samples were cleaned with an ultrasonic cleaner (Sonorex RK 102 Transistor, Bandelin) for 2 × 3 minutes with isopropyl alcohol (98%). The samples were polished by a single operator following the manufacturer's instructions. They were embedded in acrylic blocks and then placed in the chewing simulator.

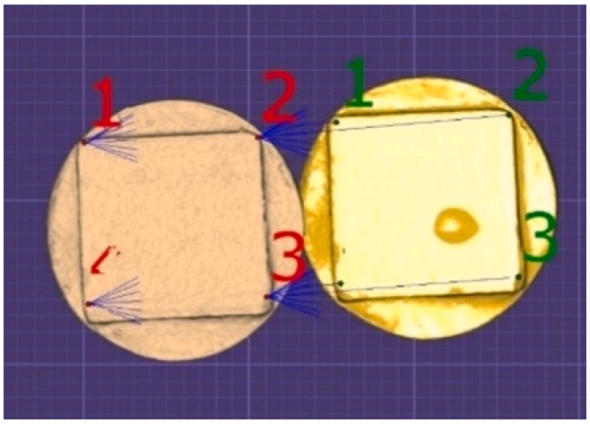


**Fig. 3.** Determining fixed 3 points for overlapping purposes.

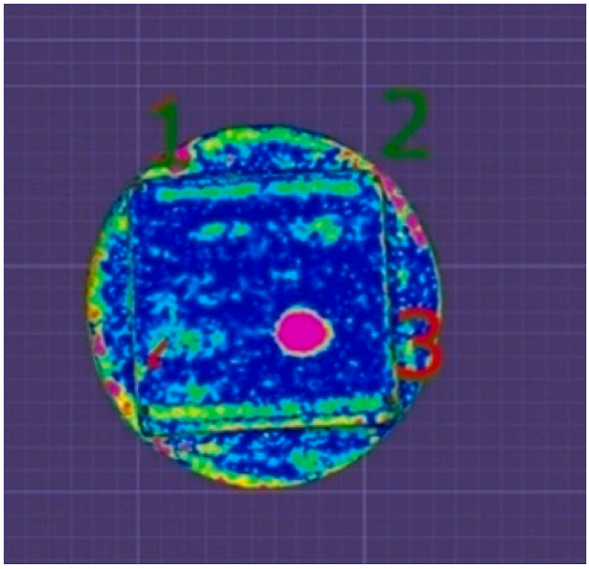


**Fig. 4.** After alignment procedure (purple colour referenced the wear area, green colour referenced good alignment areas, blue colour referenced the bit undercounter area).

### *2.3. Pre-aging surface topography characterization*

The surface roughness of all samples was measured with a profilometer (Profilm3D, Filmetrics, USA) before aging them. Average values were determined by carrying out 3 measurements for each sample. Measurements were made from the center of the samples, and the average surface roughness was calculated. The area where the measurements were taken was marked on the sample to be used again after aging. All samples were scanned with a desktop scanner (exocad Smartoptics x4, Germany) to evaluate the volumetric loss that will occur in the samples.

Before the scanning, a guideline was created with a diamond bur to achieve a correct overlap after aging (Fig. 2).

One sample randomly selected from each subgroup was imaged with SEM (Hitachi S-1520, Tokyo, Japan) at 1000× magnification. The device was calibrated after each measurement. The resulting data were stored for comparison with the post-test measurements.

### *2.4. Thermomechanical aging*

Thermomechanical aging of the samples was performed in a specially designed 8-chamber chewing device (Multifunctional chewing simulator, Analitik Medikal, Gaziantep, Turkey) following the standard protocol. Four hundred thousand cycles were completed under a vertical occlusal force of 49 ± 0.7 N with a thermal cycle of 1.7 Hz 5–55° and with a dwell time of 120 s, mimicking 2 years of aging [25–29]. We made sure that the force pin of the chewing simulator is targeted to the area where the profilometer and SEM images were taken before.

**Table 2**
The comparison of the groups shows.

| | | N | Average ± SD | p |
|---|---|---|---|---|
| Ra before aging | 3D | 8 | $0.18 \pm 0.04^{A}$ | |
| | GC | 8 | $0.07 \pm 0.03^{B}$ | |
| | GV | 8 | $0.20 \pm 0.03^{A}$ | 0.001 |
| | VE | 8 | $0.08 \pm 0.05^{B}$ | |
| | Total | 32 | $0.13 \pm 0.07$ | |
| Ra after aging | 3D | 8 | $0.32 \pm 0.05^{A}$ | |
| | GC | 8 | $0.13 \pm 0.04^{B}$ | |
| | GV | 8 | $0.34 \pm 0.02^{A}$ | 0.001 |
| | VE | 8 | $0.14 \pm 0.04^{B}$ | |
| | Total | 32 | $0.23 \pm 0.11$ | |
| Volumetric Loss ($mm^3$) | 3D | 8 | $0.68 \pm 0.14^{A}$ | |
| | GC | 8 | $0.40 \pm 0.11^{B}$ | |
| | GV | 8 | $0.77 \pm 0.13^{A}$ | 0.001 |
| | VE | 8 | $0.29 \pm 0.08^{B}$ | |
| | Total | 32 | $0.53 \pm 0.23$ | |
| | | **N** | **Average ± SD** | **p** |
| Ra before aging | 3D | 8 | $0.18 \pm 0.04^{A}$ | |
| | GC | 8 | $0.07 \pm 0.03^{B}$ | |
| | GV | 8 | $0.20 \pm 0.03^{A}$ | 0.001 |
| | VE | 8 | $0.08 \pm 0.05^{B}$ | |
| | Total | 32 | $0.13 \pm 0.07$ | |
| Ra after aging | 3D | 8 | $0.32 \pm 0.05^{A}$ | |
| | GC | 8 | $0.13 \pm 0.04^{B}$ | |
| | GV | 8 | $0.34 \pm 0.02^{A}$ | 0.001 |
| | VE | 8 | $0.14 \pm 0.04^{B}$ | |
| | Total | 32 | $0.23 \pm 0.11$ | |
| Volumetric Loss ($mm^3$) | 3D | 8 | $0.68 \pm 0.14^{A}$ | |
| | GC | 8 | $0.40 \pm 0.11^{B}$ | |
| | GV | 8 | $0.77 \pm 0.13^{A}$ | 0.001 |
| | VE | 8 | $0.29 \pm 0.08^{B}$ | |
| | Total | 32 | $0.53 \pm 0.23$ | |

Notes: GC:Cerasmart, VE: Vita Enamic, GV: Grandio Voco, and 3D: FormLabs Permanent Crown Resin. **Exponent letters are used to compare groups. There is a significant difference between groups with different letters.*

### *2.5. Post-aging surface topography characterization*

After aging, the samples were re-imaged with the profilometer and SEM to determine the surface roughness and to examine the surface topography using the same parameters. 3D scans were repeated to identify the physical volumetric loss. To overlap the resulting 3D scan data, a fixed point was determined on the 4 corners of the samples on the horizontal axis (Fig. 3).

For the vertical axis, the line previously created with a diamond bur was used. Therefore, the samples fully overlapped with one another (Fig. 4).

When completed, the overlap was vertically cut off from the previously determined reference line and converted into a solid object with the exocad tool. Consequently, the samples are standardized for volume measurement. The scan data before and after aging were imported into the inspector software (PointShape 3D Software, Korea), and the volumetric loss due to wear ($mm^3$) was calculated based on the difference between the volumes before and after aging.

### *2.6. Statistical analysis*

Data distribution was tested using SPSS (SPSS Inc., Chicago, IL, USA) software (version 9.1). Before the comparison analysis, the normality of the distribution was examined, and the test to be carried out was determined. The results of the Kolmogorov-Smirnov and Shapiro-Wilk tests showed that the distribution was not normal in Ra measurements. Since the sample size of each subgroup was below 30, the study was conducted with a non-parametric test called the Kruskal-Wallis test. The Bonferroni test was used as a post-hoc method to make pairwise comparisons between groups. The results were interpreted at a statistical significance of $p < 0.05$.

## 3. Results

The findings of the current study are analyzed in 2 parts: the evaluation of the surface roughness and the examination of the volumetric loss due to physical wear. The results demonstrated a statistically significant difference between the groups in the initial surface roughness (Ra) values ($p < 0.05$). The highest Ra value was found in the GV group, while the lowest Ra value was in the GC group. The GV group has the highest surface roughness with an average value of $0.20 \pm 0.03$ Ra. This group does not differ from the 3D samples; however, it differs significantly from the GC and VE groups. Detailed statistical results obtained from the two-way ANOVA

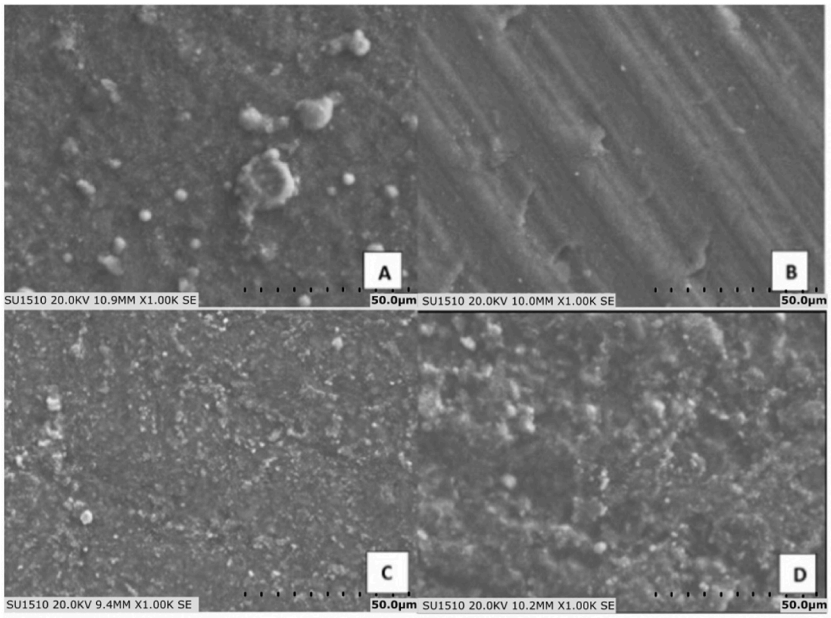


**Fig. 5.** SEM images of sample surfaces before aging, obtained at 1000× magnification. A refers to 3D, B to GC, C to GV, and D to VE group.

test are summarized in Table 2.

The second part of our study measured the initial and final volumes of the samples and calculated the volumetric loss in $mm^3$. It found a statistically significant difference between the groups ($p < 0.05$). The highest volumetric loss was found in the GV group, while the lowest volumetric loss was in the VE group. The GV group had the highest volumetric loss with an average value of $0.68 \pm 0.14$ $mm^3$. Although this group does not differ significantly from the 3D samples, it differs significantly from the other two groups.

## 4. Discussion

The current study evaluated the volumetric losses due to wear after aging and surface roughness of a recently produced composite samples fabricated with HCC blocks and 3D printing. The control group was the VE group, a hybrid material known as a polymer-infiltrated-feldspathic ceramic network. The results of the study showed significant differences in the volumetric loss and surface roughness of the restoration materials. Therefore, both research hypotheses were rejected.

In vitro assessment of wear requires scanning sample surfaces, determining the amount of wear, and performing statistical analysis based on wear measurements. As modern scanning equipment enables direct imaging of the sample surface, wear may now be identified as volumetric loss in 3D form rather than being estimated as depth in one-dimensional form or area in two-dimensional form [3]. Delong et al. reported that a 3D scanner is the gold standard in volumetric loss measurements. This method is based on the overlapping of three-dimensional images of the material before and after wear. This technique is preferred because it allows to compare data accurately, regardless of the operator and data storage. Its disadvantages are that it requires special hardware and software and has a high cost [2].

The superior mechanical properties of HCC are attributed to their improved homogeneity and controlled and optimized polymerization. Furthermore, it is generally accepted that they absorb functional stresses through deformation to a higher degree due to their low abrasiveness to antagonist surfaces and low elastic modulus [4].

HCC materials consist of certain proportions of ceramic-based particles embedded in a composite resin polymer matrix. Differences in the behavior of HCC materials are mainly attributed to the proportional volume of these two components [25]. A high inorganic phase reduces a material's tendency to absorb water, which in turn increases surface hardness and therefore increases wear resistance [3–17].

The VE group in the present study clearly showed an elevated level of wear resistance compared to other groups due to its high inorganic content. In addition to having a higher inorganic fraction, VE consists of a resin-infiltrated and interconnected inorganic glass-ceramic network. In contrast, GV is a particle-filled composite resin restorative material. This difference may explain the significantly higher wear that occurred in the GV compared to the VE one. This result is compatible with the literature [17]. The content information of the other 2 groups of materials used in the present study could not be obtained due to the privacy policies of the relevant companies.

The lower level of wear occurred in the GC group compared to the GV and 3D samples may be due to the high strength and force-absorbing qualities of GC's specially designed nano-ceramic matrix. The average filler size has been previously reported to affect the wear characteristics of composites, and smaller-sized filler particles are associated with less wear. [5],6 In other words, reduced

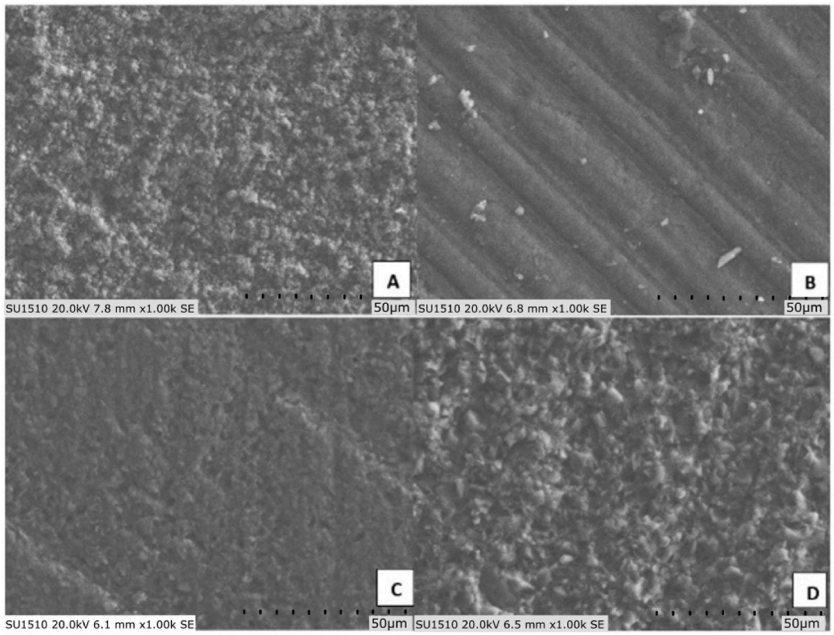


**Fig. 6.** SEM images of sample surfaces after aging, obtained at 1000× magnification. A refers to 3D, B to GC, C to GV, and D to VE group.

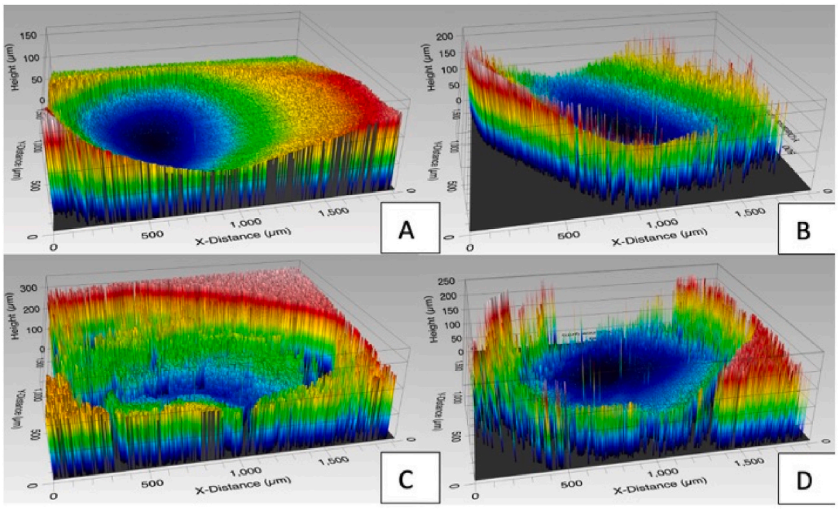


**Fig. 7.** The topography of the sample surfaces after aging, obtained with the profilometer. Images A, B,C,D show the VE, GV, GC, and 3D groups, respectively.

molecular size decreases the intermolecular distance, which makes the material resistant to abrasion [4]. The filler particles of GC are extremely small and have a significantly narrow size distribution [8]. The SEM images of the sample surfaces before and after aging in the chewing simulator are given in Figs. 5 and 6.

While the VE was the least affected material during aging, significant changes occurred in the surface characteristics of the GV group. In the GV group, the irregular filler particles are separated from the surface after aging.

The elevated level of wear that occurred in the 3D group may be explained by some difficulties in its manufacturing. 3D printed composites have specific viscosity requirements that distinguish them from CAD/CAM ones. After each exposure cycle, the platform is raised to allow the resin to flow into the space between the platform and the barrel. When the viscosity is increased with fillers, gravity and surface tension will no longer allow for a smooth surface, resulting in incomplete printing of the object. For this reason, the total volume of the fillers (i.e., the inorganic percentage) is maintained at much lower proportions to keep the material flowing [20]. The wear behavior of the 3D group, however, may not be explained solely by particle size and percentage of inorganic content. Some parameters, such as curing, wavelength, layer thickness, printing direction, and orientation of support rods in the printing process, also

affect the mechanical and physical characteristics of the composites at stake. Further research is needed to evaluate these other factors.

Surface roughness is another crucial factor related to the material influencing the wear of restorative materials. High surface roughness may lead to the development and spread of superficial cracks that can diminish the strength of a restoration [13].

Chung et al. reported that if the Ra values exceed the critical threshold of surface roughness, the composites should be polished again, and they defined this threshold value at 0.2 μm [12]. Another study reported that Ra values of 0.5 μm or higher could be detected by the patient's tongue [14]. Although the material groups used in the present study were polished following the manufacturer's instructions, there are significant differences in the initial surface roughness values (0.038–0.237). This result is compatible with the literature [15]. The high initial surface roughness of the 3D group may be due to the support rods coinciding with the area measured with the profilometer during printing.

After aging, the groups other than the VE and GC groups had Ra values greater than 0.2. Therefore, we deemed it appropriate to invite the relevant groups to regular follow-up appointments for polishing. These appointments will help restore the surface smoothness of restorations. The 3D image of the profiles formed due to abrasion on the sample surfaces is given in Fig. 7. Profilometer measurements were taken from the areas where the 2x2-mm pin of the chewing simulator coincides.

While the VE group has the lowest roughness values, the values of the 3D group are significantly higher. When the initial and final Ra values were compared after aging, the biggest difference occurred in the GV group. This phenomenon can be attributed to potential water absorption during water storage and thermal cycling, which may cause swelling on the sample surface. Some studies have reported that ceramic-network materials, such as VE, are less affected by aqueous conditions and thermal cycling [9,10].However, a study on aging with a thermal cycle found that resin-based materials were more affected by thermocycling. The application of the thermal cycle simultaneously with mechanical loading in the current study explains this phenomenon [11].

Due to the errors that may occur in standardization, an enamel antagonist was not used, and therefore the wear on the opposing arch was not analyzed. Distilled water was also used instead of saliva in the chewing simulator. These are the limitations of the present study.

## 5. Conclusion

Within the limitations of this current study, the following was concluded.

- Polymer infiltrated ceramics such as VE are more successful than other material groups in terms of wear-related volumetric loss.
- From the tested restorative materials, it can be said that VE and GC groups are suitable for long-term restorations, while the GV group is suitable for medium-term restorations. The similar results of the 3D material with the GV group are promising for 3D printing technologies

## Additional information

No additional information is available for this paper.

## CRediT authorship contribution statement

**Neslihan Güntekin:** Writing – review & editing. **Ali Rıza Tunçdemir:** Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: NESLIHAN GUNTEKIN reports financial support was provided by Necmettin Erbakan University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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